Invent or Discover

the art of useful science

[Sample Chapter 1: Nuclear fusion electricity]

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alanrwalker books, Edinburgh, 2012, http://www.alanrwalker.com
ISBN: 0-9545173-1-8,
Kindle edition: http://www.amazon.co.uk/dp/B007IHCFSS

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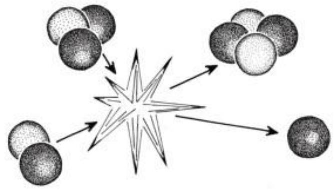

‘*Should the research worker of the future discover some means of releasing this energy in a form which could be employed, the human race will have at its command powers beyond the dreams of scientific fiction . . .* ’

(Francis W. Aston)

On the wooded plain near the town of Cadarache, close to Marseille in the south of France, a new electric power station is being built. This will be a strange sort of generator of electricity because it will produce power just in bursts measured in seconds and minutes, interspersed with gaps measured in days. It is the International Toroidal Experimental Reactor, started in 2006. When ready to operate in its plain square cut main building there will be an extraordinary assembly of a colossal circular vacuum tube surrounded by a complex array of electro-magnets in opposing alignments. The magnets cooled with liquid helium will have their circuits made efficient by superconductivity. Inside the vacuum chamber, the particles that make up a special type of hydrogen will form into a ghostly wisp at a temperature far hotter than the core of the Sun. The magnets will force these particles away from the walls of the chamber, preventing it from melting. The extraordinary heat will force the particles together so strongly they will fuse to form atoms of helium. In so doing their mass will diminish minutely. This loss of mass will convert directly to energy at the almost incredible rate predicted by Albert Einstein in his famous equation: multiplied by the square of the speed of light.

The plan is to find out how to make this reaction proceed so well that it produces far more energy than has to be supplied for the magnets and heating. Many years after that, another machine will need to be built to devise a way to extract this energy, much of which will be given off as atomic particles which will penetrate the massive metal wall of the vacuum chamber and be absorbed in a sort of blanket. There the heat will be trapped, to be rapidly removed by circulating ordinary helium gas through it. That hot gas will then boil water for a steam turbine, which will drive ordinary electricity generators. Engineers will gain experience from that prototype to determine the design of the first full power plant. The generators, connected to the national grid, will enable sale of electricity to ordinary commercial and domestic customers. Eventually the first working nuclear fusion plant will have been created.

The long way remaining to travel with this idea needs to be measured not from when it was first formulated in a patent application in 1946. Further back, any one of a small group of physicists studying the behavior of atoms, could predict that atoms could fuse and thus release these vast amounts of energy. That was about 1922. Some physicists refused to accept that reactions at this atomic level would ever lead to useful production of energy. Other physicists lit a flame of hope that has been burning bright all these years. What is it about nuclear fusion that has maintained such faith all these decades?

Mass defect

This story has many origins, but the mystery of cathode rays is central. Devices creating these rays were fascinating, not just an experimental tool of physicists but a party trick to entertain the public. Originally called Crookes tubes, they were a large pear shaped glass vessel in which a vacuum was created. An electric voltage was applied to two electrodes in the vessel and the rays emanating from them streamed to the end of the vessel where they induced an entrancing patch of glowing light within the glass. Cathode ray machines continued to be developed by manipulating the rays with magnets to create images on a fluorescent screen. You may remember them as an old style television or a computer monitor – the kind with a bulky magnet housed behind the screen, heavy and awkward to lift.

Joseph John Thomson was a physicist determined to discover what these rays were. In doing so he could be described as the first person to 'split the atom', although 'knocking off a bit of it' would be more accurate. Whatever, J.J. Thomson redefined these cathode rays as electrons and in doing so first proved that the indivisible atom of chemists consisted of sub-units. He demonstrated that electrons are particulate; that is they have mass, although a minute fraction of the main mass of the atom. In his laboratory, the original Cavendish in the center of Cambridge, England, Thomson had built an apparatus to weigh atoms, a mass spectrograph. His was not the first attempt to do this but his design was, by intended use, a forerunner of the modern mass spectrometer.

Thomson and his team used the new apparatus to make a preliminary catalogue of the elements, based on their atomic weight. (It is simplest for this story to refer to weight of atoms, as did the original researchers, rather than their atomic mass because definition of the term atomic mass has to cope with many complex difficulties.) They did not weigh single atoms of course, but measured them relative to a comparator element: hydrogen, oxygen, or now a particular form of carbon. Their approach contrasted with the ordering of elements by their chemical properties, as in the Periodic Table devised a few decades earlier by Dmitri Mendeleev. They included in their study some of the inert gases that can be found in the atmosphere, made available by James Dewar from his samples of liquefied air.

When it came to a sample containing neon, the gas that gives such a gorgeous red glow in advertising displays, the result was unexpected. The data from the spectrograph came in those days on photographic plates, looking a bit like white on black photographs of a firework display. Next to the main streak of white indicating neon was a faint parallel streak. Thomson proposed that this was an isotope of neon. That is, a form of neon with different mass from the usual element. Isotopes had already been discovered by Frederick Soddy after a long and complicated struggle to understand the nature of elements that are radioactive and naturally unstable. Never before had isotopes been associated with elements as stable as neon.

Thomson the physicist handed over the mystery of neon to Francis W. Aston, a chemist. Aston built a better mass spectrograph for the job (it was a design made a little early by Arthur J. Dempster at the University of Chicago, that became the definitive one to evolve into modern machines). By 1920 Aston soon produced a long table of the elements based on their atomic weights, and these data were in neatly in whole numbers, or very nearly so. Thus the elements could be arranged in a simple list of atomic number.

One stark anomaly remained; the starker the questions it raised the deeper the mystery. It was not new, chemists had long known the experimental facts and Aston's accurate measurements meant they could no longer gloss over the anomaly. The problem was crucial because it lay with hydrogen, the simplest element consisting of a nucleus of one proton (positively charged) surrounded by one electron (negatively charged), a basic unit for all the others.

They knew this to have a weight not of exactly 1 to match its atomic number of 1, but of 1.008. Easy to miss, easy to blame on inaccurate measurement, but now that point 008 could no longer hide from the probing of the latest instruments. Helium behaved as it should: the next element down the table, at atomic number 2 with weight of 4, and so on. However, since helium was by then understood to comprise the equivalent of four hydrogen atoms, where had the extra 4 x 0.008 gone? Physicists came to know this problem by the name of Mass Defect. That is, there was mass missing from the sub-atomic particles making up an atom of helium.

A deep and bewildering hole for these researchers to have dug for themselves, but with a possible escape along a mind boggling route. By then, Albert Einstein's proposition of the equivalence of mass and energy (energy equals mass times the square of the speed of light) was well established as a working hypothesis amongst physicists. Furthermore, they all accepted the principle of the conservation of energy: it is neither created nor destroyed; not ever in the past or the future. Energy is fundamental, it simply exists. There was left only one plausible answer to the anomaly of hydrogen's mass.

An amount of energy equivalent to the missing mass, all 0.032 of it in a helium atom, had been converted into energy when helium was formed from four hydrogen atoms. Aston used a simple calculation to illustrate the point: the amount of hydrogen in 9 milliliters of water, if fused into helium would release 200 gigawatt-hours of energy. The laconic style of University of Cambridge academics was for once inadequate for the significance of such a calculation. The very matter-of-fact Aston was inspired to venture in his Nobel Prize lecture: 'Should the research worker of the future discover some means of releasing this energy in a form which could be employed, the human race will have at its command powers beyond the dreams of scientific fiction . . .'

The conditions under which there might be full conversion of mass into energy are strange and rare. Nevertheless, the amount of energy available from a partial conversion, say just 0.3% for a nuclear fusion, is still awe inspiring. Einstein expressed this relationship in terms of ergs for energy expended, or work done. A small domestic electrical heater will draw one kilowatt of power from the domestic electricity supply, and if left running for one hour it will transfer one kilowatt-hour of electrical energy into heated air. That domestic electricity is likely to be supplied by a coal-fired power station, which typically come big for economies of scale, capable of generating one million kilowatts, or one gigawatt, of electrical power.

Einstein's equation predicted that one gram of matter, about the weight of a typical banknote and of any kind of matter, is convertible into work by the vast multiplier of the square of the speed of light, giving a total of 24.9 million kilowatt-hours. Imagine that same power station running full blast from midnight to midnight, driven by the nuclear combustion of a lump of matter the size of a dollar bill. This is, for a perfect conversion of mass to energy, three trillion times more energy than can be released by chemical combination, ordinary combustion, of one gram of carbon and hydrogen in that coal, with the oxygen in air. Albert Einstein provided the mathematical basis for the incredible speculation of Francis Aston. Experimental proof was then needed.

Laboratory fusion

The astronomer Arthur Eddington, after his observations of the bending of light from our Sun during an eclipse, thus proving Einstein's general theory of relativity, speculated how the stars radiate so much energy. Chemists then understood chemical combustion to be incapable of supplying such vast energy. Something else had to be happening in a realm beyond ordinary oxidative reactions between molecules. Eddington, as a champion of Aston's discovery, suggested that if hydrogen atoms in the sun are being combined to form helium, then the excess mass can only be transformed into energy.

Yet another fine challenge was clearly in the public domain: explain the source of heat and light from the sun, explain how it lasts for aeons. An early explanation linked three concepts: structure of atoms, mass and energy being equivalent, and the weird idea of quantum tunneling. The last was crucial; it allowed the possibility of light atomic particles in the form of protons from the nucleus and associated electrons, to penetrate into a nucleus of helium. This could occur at the temperatures predicted by Eddington. An unstable intermediate would be created, only to decay into two helium atoms. The mass of this pair would be less than the mass of what went into creating it. The disappearing mass would re-appear instantaneously as energy – astronomical amounts of it.

Quantum tunneling may be more familiar to you as the phenomenon exploited in the manufacture of flash memory sticks. In the late 1920s the concept was incubating as a brilliant extension of the consequences of the quantum mechanics relating to atomic structure. George Gamow, then working in Göttingen and Copenhagen, and Ronald Gurney and Edward Condon in America, proposed that there was an exceedingly low chance that a sub-atomic particle moving toward a nucleus could penetrate *through* it rather than bounce off such a dense object. Only a minute chance, but all the researchers needed to prove this would be to bombard the nuclei under study with a dense stream of sub-atomic particles for long enough.

They suggested using a force of several hundred thousand volts to accelerate protons. Gamow was a playfully imaginative researcher: translated, the title of his paper referred to an 'atom-smasher'. Gamow moved for a while to work at the Cavendish laboratory where he discussed the practical application of this concept with John D. Cockcroft and Ernest T.S. Walton. Soon they were to show that smashing atoms was not really the essence of what was going on. Something of subtle difference but of shocking power was about to be revealed.

At the Cavendish lab, this concept of quantum tunneling provided a tantalizing prospect. If it was real, the researchers could construct a powerful new machine for probing atoms. Until then probing the innards of atoms had been done with alpha particles. These are naturally given off by some strongly radioactive metals such as radium and consist of two neutrons and two protons. They have a positive charge and so can be manipulated into a vague beam. This technique had long been a mainstay of work at the Cavendish by physicists such as Ernest Rutherford, using astonishingly simple apparatus.

Instead, an intense beam of protons could be projected at specific targets. The lab started to move into the big-time. Cockcroft and his team, especially with Ernest Walton, moved from a device that could fit in the palm of Rutherford's hand to that requiring the commercial engineering of Metropolitan-Vickers Electrical Company. So the electrics were up to the task, but for glassware of sufficient size and robustness the team were forced scavenge the large glass tubes used as 20 gallon measuring flasks on early roadside gasoline pumps. The team stuck these together in a stack of four, nearly four meters tall, using children's modeling clay, then pumped out the air to make one stack containing an electrical device to provide energy as voltage, and in another shorter stack a chamber in which the proton beam could be accelerated and directed.

Their main difficulty was to obtain sufficiently high electrical potentials to accelerate the particles, so they designed and built thermionic rectifiers and condensers for the purpose. That enabled them to work in ranges of up to 800,000 volts of steady potential, which they applied to the vacuum tube down which the protons would accelerate. Alpha particles naturally travel at about one tenth the speed of light; this was a forbiddingly high speed for their protons to match or exceed. They directed their protons at sheets made of a range of metallic elements, held in a detector screen of fluorescent zinc sulfide. The team started with the metal lithium: a choice of great portent.

This machine, a particle accelerator, grew to fill a large laboratory to its extra high ceiling. The vacuum pumps to evacuate the two towers of glass had to be fitted beneath them, under the floorboards. The glass components were subject to frequent puncturing by stray electrical discharges and the high voltages made work a hair-raising business. Results were recorded by someone sitting in a curtained dark box at the base of accelerator tube with a microscope trained on the screen to record the flashes from collisions. The field of sub-atomic particles now needed engineering skills as much as understanding of the mathematics. Nevertheless, these were still the halcyon days when the researchers could acknowledge their host university for paying for the machinery.

Cockcroft and Walton rapidly published their findings. They did not say that they had proved Einstein’s famous equation, they did not even mention Einstein or the equivalence of mass and energy. They said nothing about generating electricity. They simply stated that excess energy was produced in the form of pairs of alpha particles forced from the lithium with a total energy represented by 17 million volts. Energetic indeed, but there were very few of the particles so the energy that Cockcroft and Walton pumped into their machine was vastly greater than the energy of the alpha particles.

The crucial point was that they achieved this not by ‘smashing atoms’ as popularly reported, or even by disintegrating them as they called it. What they had actually done was to fuse their accelerated protons with the nuclei of lithium atoms. This produced helium atoms of lesser mass, and that missing mass was converted into energy. Not only had they experimentally proved what was becoming the most famous equation in the world. They had built a machine according to a theory, then used it to artificially transmute an element by a nuclear fusion reaction. That fusion released energy, which in proportion to the scale of the nuclear particles involved, was astronomical in scale.

Francis Aston’s mass spectrograph gave a huge boost to the business of predicting and searching for isotopic forms of elements. How can these elements be arranged in a plausible table and what does the table tell us about how they relate to each other? The biggest question was: how did all these elements come into being in the first place? Then, researchers accepted that elements must have originated in the stars, presumably starting with hydrogen as the simplest element. Smaller units of this problem of what happens inside stars needed to be tackled using methods near to hand or easily invented in the laboratory. Two researchers in the University of California, R.T. Birge and D.H. Menzel, had made some calculations based on data available of the natural occurrence of the known isotopes of oxygen. When the exact atomic weight of hydrogen (H-1) relative to the standard comparator oxygen (O-16) equal to 16 units of atomic weight, was compared with the chemical atomic weights of a natural mixture of oxygen isotopes, they reached the tentative conclusion that an isotope of hydrogen (H-2) might occur in a proportion of 1 part of H-2 to 4500 parts of H-1. Their estimates were at the borderline of experimental error, the fourth decimal place, in the chemical determination of atomic weights. Nevertheless, a prediction as bold as an isotope of hydrogen was too good to miss for anyone who could devise a way of testing it. New elements to discover were by then becoming hard to find but new isotopes were a good substitute.

Harold Urey, at Columbia University, New York City, had mused about isotopes of hydrogen. They would be extraordinary; after all hydrogen for long had been regarded as a fundamental unit of chemistry, not the type of thing subject to variants. New names would be justified for them – deuterium for H-2, tritium for H-3; and to complete the trio, protium for ordinary H-1. Urey gained access to newly installed apparatus for liquefying gases at very low temperatures. He predicted a minute difference in the rate at which the ordinary light isotope of hydrogen, compared to the heavy isotope, would evaporate from of an ordinary sample of liquid hydrogen. The heavy isotope, deuterium, should be left behind in the liquid. Urey and his assistant G.M. Murphy used four liters of liquid hydrogen, slowly evaporated it down to one milliliter and measured the mass of the remaining material. They confirmed the existence of deuterium.

Soon Urey's former doctoral supervisor, Gilbert N. Lewis, used a recently invented method for obtaining large amounts of deuterium. He based this on the assumption that it would occur naturally in water. If he could split a bulk of water into its constituent hydrogen and oxygen by passing an electric current through it, then the heavy isotope of hydrogen should become concentrated in the remaining water as the lighter hydrogen bubbled off. Lewis used a lot of electricity to reduce a lot of water down to one hundred thousandth its original volume. He gained water consisting almost entirely of deuterium oxide, rather than almost entirely of dihydrogen oxide (plain ordinary H_2O). All this labor and expense was to follow just a hunch; no hypothesis or formal program of research. They all understood enough about how research proceeds for confidence that this weird stuff was bound to be a goldmine of data, inspiration and experiment. Prod it and poke it with an atom-smasher for a start.

Lewis would go on to do just this, using deuterium to bombard nuclei to be investigated in a new type of particle accelerator recently invented by Ernest O. Lawrence at the University of California. This was a compact circular construction that could accelerate protons to fantastically high speed in a spiral path between a pair of magnets – the first cyclotron. Energies of the protons were measured in millions of volts for an input of just normal mains voltage. The original machine was just four inches in diameter but they were soon to grow massive as a crucial tool for research in nuclear physics.

However, to follow our story the linear accelerator of Cockcroft in the Cavendish lab remains the route. A new arrival there was Marcus L.E. Oliphant from Australia (always known as Mark); recently Rutherford had inspired him at a public lecture. Oliphant completed a doctoral study in Cambridge, using protons to study metallic surfaces. By then the huge significance of Cockcroft's atomic machine for investigating the innards of nuclei was apparent, and Rutherford supported Oliphant in an effort to build a more powerful and sensitive particle accelerator.

The machine went through various modifications and by 1934 it was capable of producing a more intensely directed beam of protons capable of hitting a target just one centimeter square. It fired one thousand times more particles at the target. Moreover the researchers now had access to a variety of what they called ‘disintegration particles’ of twice the mass, and thus twice the atom-smashing momentum, than the humble proton. From Gilbert Lewis came the precious gift of a few milliliters of heavy water, in which 93% of the molecules of water consisted of deuterium oxide. Pure heavy water literally weighs 10% more than the ordinary kind. As was usual in those innocent days, Lewis had sent samples to various potential collaborators.

Oliphant and his team set about firing protons, and what they called diplons (a nucleus of deuterium stripped of its electron) at a range of materials. They tested light elements such as lithium, boron and beryllium; heavy elements such as gold, lead and uranium. They accumulated a mass of technical data on how to accelerate particles, and noted that lighter elements were most productive. They tried ammonia in the form of salts; ammonia contains three hydrogen atoms in a pyramidal bonding with nitrogen. First they found little of interest, but why not synthesize an ammonium salt using deuterium to substitute for the hydrogen and bombard that with deuterium ions? The effect was enormous: deuterium combined with deuterium to form an unstable isotope of helium which immediately split into hydrogen and a new isotope of hydrogen. In modern terms: nuclear fusion. (The new hydrogen isotope was tritium and the new helium isotope was helium-3.) Oliphant calculated that the excess mass left over from this reaction was transformed to energy represented by 23 million volts. Not bad for a 33 year old researcher on his first postdoctoral project.

Obviously, Rutherford was a major inspiration for this dive into the depths of nuclear structure, but was he interested in the implications of Oliphant’s findings for electricity generation? No, not in the slightest; or possibly he did not want to know. In 1933 at a meeting of the British Association for the Advancement of Science, he is reported to have said: ‘We might in these processes obtain very much more energy than the proton supplied, but on average we could not expect to obtain energy in this way. It was a very poor and inefficient way of obtaining energy, and anyone who looked for a source of power in the transformation of the atoms was talking moonshine. But the subject was scientifically interesting because it gave insight into the atoms.’

Three years later he entrenched this opinion in a lecture to celebrate the bicentenary of James Watt, of all people. Rutherford was not the only skeptic: Frederick Soddy, as late as 1947, remained unconvinced that nuclear power plants would be practicable. Blessed with hindsight it is easy for us to laugh at those bold enough to make predictions, especially about limitations to the future of technology – in 1902 William Thomson (Lord Kelvin) infamously declared aircraft to be impossible. Rutherford’s failure of technological imagination reveals is that he and most of his peers, certainly including Cockcroft and Oliphant at the Cavendish laboratory, did not think in terms of utility. Most of them were excellent technicians, able to invent completely novel apparatus to test their arcane theories by measuring extraordinarily fine differences in behavior of infinitesimally small objects. They were not, however, industrialists. Their scientific theories were what excited them; published papers describing their results and conference presentations were their products, not machines they could define as useful by selling them to people who needed them.

A researcher with a different viewpoint was Leó Szilárd, an outsider to the unworldliness of academics. So exasperated was he by Rutherford's aloofness that in 1934 he applied for a patent for a nuclear power generator. The idea was to manipulate a newly discovered nuclear particle to induce chain reactions that would release energy. This was not a patent for a nuclear *fusion* reactor based on existing understanding of nuclear fusion; nor was it for a nuclear *fission* reactor because that phenomenon was completely unknown in 1934. The application was granted two years later although, for reasons of military security, publication was withheld until 1949. Szilárd had worked in the Institute for Theoretical Physics of the University of Berlin, but fled to London in 1933. By the time his patent application was granted he assigned it to the British Admiralty; a vessel needing to cruise the oceans for long deployments would be a good place to install one. The history of nuclear power, with its obvious potential for big bombs, was about to be cloaked by military competition. Despite that, by the mid 1930s there was both the established concept of controlled nuclear fusion to generate power, and a patent for another very different route to nuclear power production.

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In 1932, at the University of Liverpool, James Chadwick discovered a new particle within the nucleus. This was what Rutherford, Chadwick's former colleague, had tentatively called a 'neutral hydrogen atom' 12 years earlier. Without an electrical charge, they named it neutron. At the stroke of a new discovery they could at last explain isotopes. These have varying numbers of neutrons, affecting atomic weight without affecting chemical bonding, which depends on the electrons. Deuterium, as simplest example, has one proton and one electron just like ordinary hydrogen, but additionally has one neutron in its nucleus. More importantly for our story, the discovery of the neutron invigorated research into nuclei by providing a new technique of extraordinary power. A neutron is a constituent of all nuclei except that of ordinary hydrogen, and is as massive as a proton. However, because it lacks electrical charge it can penetrate deeply, unconstrained by repulsion from the nucleus to the charge on particles such protons.

Leo Szilárd had patented his nuclear power generator based on neutron reactions. Enrico Fermi was another of the physicists inspired by neutrons. At the University of Rome, Fermi promptly set about probing a large range of elements. A simple fact-finding investigation: stimulate beryllium powder with radon gas emitting alpha rays, all in a small glass tube. Beam the resulting neutrons at the elements then examine the activation of the elements by counting any emitted beta radiation with a Geiger counter. As Fermi and colleagues worked their way through the periodic table, they found little reaction with the lightest elements. Eventually they arrived at the heaviest element then known, uranium, their results became distinctive but inexplicably complex.

Uranium fascinated another disparate team working in the chaos of impending war in Europe about 1938. The story of how nuclear fission was accidentally discovered by Lise Meitner, Otto Frisch, Otto Hahn and Fritz Strassman, and then exploited by Enrico Fermi in the first nuclear fission chain reaction in Chicago on 2 December 1942 has been told often. Intellectually that is a separate story, but economically and politically the stories of nuclear fission and nuclear fusion continue to entwine.

Szilárd's patent for a fission reactor was, in its intent, an invention in search of the essential discovery to make it work. He was soon to see his technological inspiration supplied with the necessary breakthrough. The first plausible patent for a fission reactor was applied for by Fermi and Szilárd in 1944 and granted in 1955, delayed by military secrecy. Between 1954 and '58 fission power plants were connected to the national electricity grids at Obninsk in Russia, Calder Hall in Britain, and Shippingport in America. Soon after the end of the second world war all the basic knowledge was available for fission nuclear power generation. Bridging the plausibility gap between the 1934 and 1944 patents was due to new understanding of how to obtain power by fission of heavy elements that could be mined and purified from geologic deposits. That came suddenly and unexpectedly to a small and tenuous group, investigating the strangeness of the nucleus of uranium.

In contrast, the understanding of the possibility of obtaining power from nuclear fusions of light elements came many years before, in the early 1920s, to many individuals diffusely in time and place. That idea sprung into being without any deliberate search for ways of generating electricity. Work was started on fusion reactors in 1939 by Eastman Jacobs and Arthur Kantrowitz at the Langley Memorial Aeronautical Laboratory in America, but failed to secure funding. The first patent for a fusion power generator was made by George P. Thomson in 1946; a highly plausible one in terms of its basic science. Despite starting earlier, progress along the route toward fusion power would prove an entirely different proposition to the development of nuclear fission power. That is where we must now follow.

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George Thomson was well placed to take advantage of the rapidly expanding understanding of what was needed for fusion power, both the concepts and the equipment. He was the son of J.J. Thomson. The father considered the electrons he discovered as particles but the son, working at the University of Aberdeen, experimentally proved that electrons were also waves. That discovery had been announced just before, in 1927, by Clinton J. Davisson and Lester H. Germer at Bell Telephone Laboratories in America. Davisson and Thomson later shared the

Nobel Prize for physics for what they both acknowledged as a simultaneous discovery. George Thomson rose to an influential position during the mid 1940s and his patent, co-authored by Moses Blackman, came from his post-war base at Imperial College, in London.

Thomson and Blackman thought in practical and business terms, starting from their experience with handling ionized gases, or plasmas, to discover their secrets. The term plasma had been coined in 1928 by Irving Langmuir, from his laboratory of the General Electric Company, New York State, whilst researching on ionized gases. He wished to distinguish them as the fourth state of matter: solids to liquids to gases to plasmas, as the temperature rises. At the highest temperatures the electrons go their own way, leaving the nuclei bare; both with randomly furious kinetic energy.

Thomson and Blackman's patent was extraordinarily prophetic. They planned to construct a chamber as a tube curved strongly round to join at its ends, thus forming a ring, like the rubber inner tube of a bicycle wheel. A torus in other words. This has two sets of dimensions: the tube with its diameter and profile in cross section, and the ring that the tube forms with its diameter and overall shape. Toruses are often described as doughnuts but the analogy works best if you live in a country where someone has removed the center from the treat; in sweet-toothed countries doughnuts are spheres with a core of sugary fruit – much tastier.

George Thomson here borrowed from his father, who had used a torus apparatus to study electrical discharges through ionized gases in the 1920s. The ring would be four meters in diameter, and the tube would have a bore of 60 centimeters. The deuterium would be ionized by heating it to form a plasma and the heating would be done by electrical energy supplied as radiofrequency waves guided into a progressive wave around the torus. They expected the plasma temperature to reach many millions of degrees, at which energy some of the naked nuclei of deuterium would slam into each other sufficiently fast to overcome their natural electrostatic repulsion. These nuclei would fuse. The general type of fusion reactions now sought are to form, by the fusion of deuterium nuclei, a proton and a nucleus of tritium. The reaction should continue when deuterium fuses with the tritium to give a neutron and a nucleus of helium. The mass of the helium plus neutron is slightly less than the deuterium fuel supplied, given off as vast kinetic energy of the protons and neutrons.

Thomson and Blackman, however, foresaw a major problem. Would the balance between the power produced from the few fusion reactions and the power needed for heating the plasma and activating the magnets be favorable? Moreover, times were bleak. Britain in the late 1940s was exhausted from the war and could scarcely find resources to feed for her people let alone buy fancy engineering equipment for university researchers. All Thomson could do was farm out his fusion reactor ideas to doctoral students, equipped with little more than some large glass tubing and war-surplus electromagnets and condensers.

These ideas for manipulating plasmas did not appear out of the blue. By the late 1930s there were many clues circulating. The interest in the effects of passing an electric current through a thin gas in a vacuum tube had grown into a major sub-discipline called plasma physics. The discovery of deuterium and its amazing properties spurred the field onward. Could it be possible to heat a plasma so much that controllable fusion reactions might occur? But how to prevent such a fantastically hot material, even if so vaporous and ephemeral, from melting its container?

One clue for a way to keep the plasma away from the walls of its container came from a nearly forgotten and unlikely source. A paper published in 1905 described observations made in Australia of how a lightning strike onto a copper tube crushed the tube, as if it had been sucked inwards along its length. This became known as the pinch effect. The observation intrigued the imagination of a student at the University of Sydney – Peter C. Thonemann. As early as 1939 he had proposed using this effect to confine a plasma in which controllable fusion reactions could occur.

Supported with a scholarship from Imperial Chemical Industries, Thonemann arrived at the Clarendon laboratory of the University of Oxford in 1946 to study for a doctoral degree. His supervisor thought he should study something more sensible than inventing nuclear fusion reactors, so Thonemann pursued his enthusiasm for them independently. He persuaded the director of the laboratory to arrange for their glass blowers to construct large toruses. They pumped the air from them and replaced it with a small amount of hydrogen gas at very low pressure. A wire was coiled around the outside of the torus and then connected to a strong radio transmitter. That induced a strong current to flow through the plasma within the torus. The current flowing through the plasma induced a magnetic field and the interaction between the current and the field produced an inward force, the pinch, to contain the plasma.

By 1948, the managers of the Atomic Energy Research Establishment in Britain had taken an interest in Thonemann’s experiments, supporting him with equipment then putting him on their payroll, complete with a team of researchers. A roomy laboratory was set up in disused aircraft hangars at Harwell, 25 kilometers south of Oxford. Thonemann’s ultimate boss was John Cockcroft, and the potential of fusion power that he had demonstrated was too attractive to ignore, despite the urgent need to produce a functioning fission reactor. By 1950 patent applications for nuclear fusion power generators were being made by Thonemann from Harwell.

Meanwhile, George Thomson, now in the University of Cambridge, had set two doctoral students, just returned from military service, the task of following a lead from Germany. There the physicist M. Steenbeck had produced a device for manipulating plasmas, called the Wirbelrohr, or whirl tube. Stanley W. Cousins and Alan A. Ware split the work, with Ware constructing a small toroidal chamber, just 25 to 40 centimeters diameter, coated with metal. Through this, a strong current would be discharged to accelerate electrons. Cousins studied the pinching of the plasma and by 1949 produced a machine demonstrating containment of a plasma by controlled pinch effect in a toroidal chamber. This technical first vindicated the patented design of Thomson and Blackman. These plasmas, however, were lively, fickle things and none of the devices of Thoneman, Ware or Cousins could control adequately what seemed to be inherent instabilities which led to extinguishing of the plasma as it wriggled and wavered into the walls of the torus chamber, leaking away its crucial heat.

Despite very tight security surrounding the nuclear physics of bomb making in America and Russia, knowledge of the physics of making either a bomb or an electricity generator using nuclear fusion reactions was mainly in the public domain. Obviously secret were the precise engineering designs. Fusion for constructive purposes remained during the war years mainly an academic research, constrained by shortages of material and skilled people. By the late 1940s, however, it appeared that fusion power generation was not only theoretically possible but the engineering practicalities were now a plausible research challenge. Surely the allure of vast amounts of electrical power from water as the fuel would attract generous funding? Sure enough, cash soon cascaded on a wave of confidence and economic activity, accelerated through the experience of a war where multiple technological supremacies had been a winning strategy.

At Princeton University's department of astronomy was an astrophysicist, Lyman S. Spitzer. In the late 1940s he was studying the theory of fusion bombs in conjunction with projects at Los Alamos. Reports of ambitious plans for fusion power generators stimulated him to request extra funds and permission from the recently formed Atomic Energy Commission for research on a fusion power generator. Work had to be done in secret, in a large shed owned by the university, formerly used to house rabbits. Spitzer's proposition was novel; he was a fountain of creative enthusiasm, already working on ideas that were to lead to the Hubble Space Telescope.

Instead of relying on the pinch effect, which was simple but already known as having difficulties in controlling a plasma sufficiently, he would confine the plasma in a metal torus surrounded by many independent magnets as separate rings, each around the circumference of the tube of the torus. They provided a strong magnetic field running along the length of the torus ring. This is known as the toroidal field. Additionally, along the length of the tube and within the first set of magnets were helically wound electrical cables to produce a separate weaker magnetic field, running around the circumference of the tube. This is known as the poloidal field. The interaction of the two magnetic fields would produce a slight spiral twist to the combined field. Their combined magnetic effect forced the electrically charged particles of the plasma away from the walls of the torus tube. The problem of the plasma drifting away from its confinement and colliding with the tube was serious. So in the original design the torus was not be a simple ring, but an oval with a single central twist of 180 degrees to form a figure of eight. The twist would equal out the tendency of the plasma to be pulled always to one side if in a simple flat torus. To heat the plasma, intense radio waves were beamed into the torus tube to transfer energy.

The engineering of fusion generators was about to become much more complex than the early pinch effect devices. Spitzer's prototype, however, was a mess of wooden supports, a small glass tube for the torus, crude electrical wirings and switchgear, all fitting on a tabletop; at first glance, more like something cobbled together in a private garage on Sunday afternoons. Ever the optimist, Spitzer alluded to the Sun, calling it the Stellarator. By 1952 it was producing its first plasmas and by 1954 a second model was running capable of heating the plasma to one million degrees. The big problem, however, was the length of operation. The fully heated plasma would self extinguish after a few milliseconds. Despite the confining magnets the plasma thrashed as a frantically electrified snake. As the plasma touched the walls of the tube, it lost heat and vanished; an ephemeral wisp.

International project fusion

Nikita Khrushchev became the First Secretary of the Communist Party of the Soviet Union in 1953 and started a move away from the paranoid secrecy of Joseph Stalin. One astonishing example of this new era was a delegation to the laboratories at Harwell during a state visit of Khrushchev to Britain in 1956. Also included was nuclear physicist Igor V. Kurchatov. Since 1938 he had been director of the Nuclear Physics Laboratory at the Leningrad Physico-Technical Institute and by 1943 he was working in Moscow at the Institute of Atomic Energy.

Krushchev instructed Kurchatov to give a talk to the assembled researchers. Despite avoiding practical detail, Kurchatov clearly outlined the considerable and remarkably parallel research in Russia on fusion power generation since 1950. He referred to the basis of Russian ideas on fusion generators having come from a pair of relatively unknown theoreticians: Andrei D. Sakharov and Igor Y. Tamm. The meeting was stiff with hesitancy about asking anything of the Russians that would reveal how much the British knew. Nevertheless, Krushchev's bold venture opened a wide door through what was otherwise to remain known as the Iron Curtain. The Russians had concluded that the peaceful uses of this form of nuclear power were both of such enormous potential but of such great technical difficulty that the open circulation of research knowledge and ideas would be of benefit to all. They thought it best if the whole field could be opened up, clearly moved away from its morbid association with bombs, and include formal international collaborations to share the financial burdens. None of the Russians would admit it, but the cost of technological competition with America was hurting badly.

What the delegation were shown at Harwell was the makings of a machine called ZETA, a snappy acronym that on closer inspection revealed quirky diffidence: the *zero* energy thermonuclear assembly. By 1957 Zeta was operational as the largest experimental controlled fusion machine in the world. The machine was the most advanced embodiment of the research on pinch effect machines. It consisted of a circular torus with a metal tube 24 centimeters diameter and torus ring of 2 meters diameter. Through the center of the torus ring and coming out at one side was a colossal curved iron transformer. This formed the primary circuit of an induction magnet. It was activated by a massive pulse of electricity from a bank of capacitors. When fired up this magnet induced an electric current in the plasma. In turn, that current induced a magnetic field at right angles to it. This was the poloidal field and because it was formed by the electric current in the plasma it had a strong pinch effect, pulling the plasma away from the walls of the tube. The strong current also heated the plasma through electrical resistance, as in the conductive element of a domestic electric heater. Around the circumference of the tube, were fitted numerous circular magnets, spread evenly around the torus ring. These induced a magnetic field at right angles, thus going along the length of the torus ring. This was the toroidal field. In contrast to the competing Stellarator design, the poloidal field of Zeta was much stronger than the toroidal so here a strong spiraling was imparted to the combined field.

United States President Dwight Eisenhower had initiated through the United Nations a conference in Geneva in 1955 to discuss collaboration in peaceful uses of atomic energy. The second such conference was due to be held at the same venue, in 1958. Collaboration may have been the aim of the politicians concerned with paying for this burgeoning research and wishing to de-fuse cold war tensions. The researchers had additional agendas; they could not resist the opportunity to out-compete each other. Moreover, this was the year of the first satellite, the Russian Sputnik. Delegates from the Atomic Energy Commission in America were determined to show the Russians that they had more important advanced technology to offer the world than a tiny satellite that only went bleep bleep. The British researchers were in on this as well, agreeing with the Americans to a moratorium on publishing results in the year leading up to the conference.

With one exception: it was was announced with a great fanfare of publicity timed to coincide with a meeting of the British Association for the Advancement of Science in September 1957. This was reported with restrained enthusiasm by a few serious newspapers and trade journals. By January this news lead was circulating amongst journalists and at a press conference John Cockcroft was unwise enough to be pressured into claiming ninety percent certainty that Zeta had achieved controlled thermonuclear fusion. Newspapers in Britain printed front-page stories of an imminent supply of electricity so cheap it would not be worth the cost of metering it; presumably with a bit of taxpayer’s money encouraging the steady flow. Britain was in need of a technological morale booster. Sputnik had been salt into the wound of Britain’s struggles with rocketry and the press eagerly amplified the naive optimism of researchers and public. Strangely, this was despite the fact that by this time Britain had one of the world’s earliest fission reactors producing commercial quantities of electricity for the national grid, amply demonstrating the productivity of the researchers at Harwell.

Cockcroft’s optimism proved unfounded. The tendency of fusion machines to release stray neutrons was already known; Kurchatov had warned the workers at Harwell of this very point. They were not the natural product of fusion reactions but a side effect of the mechanisms for heating the plasma. It seemed that the plasma in Zeta had not actually reached the enormously high temperature that would characterize nuclear fusions. Stray neutrons had confused the researchers into premature conclusions, pressured by a demanding bureaucratic machine and a voracious press. A mistake they probably would not have made in an open and declassified system of announcing results in scientific journals and conferences.

By the shores of Lake Geneva five thousand researchers and officials from sixty seven countries convened in September 1958. Most of them were there to talk about fission power generators, but also on show in the exhibition hall were working versions of the Stellarator in its B version and a full-scale model of the new C version, also a pinch effect machine from Russia that operated in a straight tube rather than a torus. The Russian exhibit was backed up by photographs of a similar machine 20 meters long. This had enormously powerful magnets at both ends to constrict and contain the plasma within the tube by reflecting it back, like a mirror. One version of this was called the Probkotron, translating in English to Plugatron. For the British, Zeta was too bulky and under a shadow to contemplate duplication at Geneva.

Paranoid competitiveness was rife, but as the conference proceeded this was ameliorated by revelations that the same research and engineering paths had been travelled by teams operating in deep or total ignorance of what the others were doing. The laws of physics and the available technological options for exploiting those laws inexorably channeled everyone into converging paths. The dawning realization of this leavened the atmosphere. The researchers spontaneously developed a collective optimism for the potential for research projects that would be far better with international funding. This second conference in Geneva was a huge success, rapidly spawning visits between laboratories, formal collaborations and increases in funding for fusion reactor projects. Political work soon produced another conference and a formal international organization, the International Atomic Energy Agency of the United Nations.

The Russians had their own fusion machines, but they also had a very important technical advance to announce. Andrei Sakharov and Igor Tamm had been working on theoretical nuclear physics at the Physics Institute of the Academy of Sciences, in Moscow in the late 1940s. The head of the People's Commissariat for Internal Affairs (the greatly feared NKVD, predecessor to the KGB), Lavrentiy P. Beria, asked them to redeploy to a remote and secret research city. When Beria asked, you agreed. Soon they were confined to working at what they all called 'The Installation', on designing a hydrogen bomb. Then, via Beria's office, they received an instruction to evaluate an idea from a young sailor in the Pacific Fleet of the USSR, Oleg Lavrentiev, who had submitted a tentative proposal for a fusion reactor. His idea was to confine the plasma electrostatically. Sakharov was quick to point out that the plasma would inevitably contact the electrostatic grid and lose its heat and charge.

However, Sakharov had spent some of his time during the war in a munitions factory where he invented several magnetically based devices for testing quality of shells. The proposal of Lavrentiev got Sakharov thinking about magnetic confinement of a fusion plasma. He enlisted the help of Tamm and the pair spent part of their time at the Installation from 1950 to 1951 making plans for a fusion reactor. Tamm’s help was crucial, he was author of a successful textbook on electricity and knew much of the theory of magnetism. Soon a commission was dispatched to the Installation to talk business. The upshot was that development of a fusion reactor would at the lab of Kurchatov in the Physics Institute in Moscow, whilst Sakharov and Tamm concentrated on getting their bomb to explode.

They were the principal theoreticians, and in Sakharov’s words knew that: ‘The physics of atomic and thermonuclear explosions is a genuine theoretician’s paradise.’ The motivations of warfare are a finely balanced game; some of the workers on the Manhattan Project for the first fission bombs had a fine time of it. These Russians, however, had recently endured another of the barbaric invasions of their country, deeply imbuing them with a sense that they had become some sort of soldiers fighting a new scientific war in their work on munitions. Bombs like these surely would deter anybody contemplating yet another invasion of their motherland.

Sakharov and Tamm’s design of reactor become known generically as tokamak, after the Russian initials for toroidal chamber and magnetic coil. Based on a torus, its pinch effect was supplemented with a massive array of magnets around the tube of the torus chamber. At first, this remained a Russian project, but by the third conference convened by the IAEA, in 1968, it was out in the open. The conference was held at Novosibirsk, a special research center in Siberia, fortunately during the summer warmth. The Russians were ebullient, proud to announce results from their T-2 and T-3 tokamaks that deeply impressed everyone. The temperature of the plasma was up to 10 million degrees and its confinement time lengthening to as much as 20 milliseconds. All this was from a machine with the torus ring only 2 meters diameter and the cross section of tube only 24 centimeters.

By now Zeta was destined for a museum piece and although there was a plethora of fusion power generators being experimented with in many more countries the way ahead for most researchers was becoming gloomy, especially with impending harder economic times. The financial boom time for research of the 1950s and early 60s was over. Many researchers on fusion power were narrowing their horizons to concentrate on the depths of plasma physics, at the expense of bold engineering initiatives. Hence news of this tokamak, incorporating much commonality with the older pinch effect machines, was a welcome announcement to some, but a competitive threat to American researchers.

Members of Britain’s delegation to Novosibirsk were more sanguine. They needed a replacement for Zeta but remained proud of its conceptual closeness to the tokomak design. The British efforts were now concentrated at a new site, Culham, close to Oxford. Sebastien Pease was now the director of the Culham laboratory and had cultivated a friendly working relationships with his Russian peers. They needed each other. One party had the best design whilst the other had invented an advanced instrument to measure unequivocally the temperature of the plasma as it was created and contained. Extraordinarily for the time, the instrument used one of the new fangled lasers. This was less than a decade since Ted Maiman had first demonstrated his ruby laser device in California, as we shall see in Chapter 6. In 1969 a cargo aircraft landed in Moscow carrying five tonnes of equipment, bound for the Kurchatov Institute where the T-3 tokamak was being readied for testing. A year later, after many complications, they confirmed the original Russian results. The entire fusion community was re-invigorated by a new design with a tenfold increase in the most crucial characteristic of performance: the temperature of the plasma.

By the early 1970s there were 17 tokomaks being built or running outside Russia, now including France and Japan. Even at Princeton University, where researchers had been particularly skeptical of the claims for the original tokamaks, the latest Stellarator was with scant regret converted to a tokomak. That in itself was a strong indication of the commonality of design constraints. Stellarator, Zeta, tokomak: they differed mainly in the engineering configuration of the system for confining the plasma rather than anything more fundamental about the reactions at nuclear level in the plasma.

This was the beginning of big science for the tokamak as a potential generator of almost unlimited power and the relegation of most other designs to the status of machines on which to research plasma physics. Some of these designs continue in use and development today, newly built stellarators are in operation for example. A complete departure from the magnetically confined reactors such as tokamak is the inertial confinement system that employs a large array of very powerful lasers protruding as fat rods from a huge metal sphere. The lasers all simultaneously focus their intense energy on a central minute pellet of fuel for the nuclear fusion reactions. The principal example of this is at the Lawrence Livermore National Laboratory in California, but it is a design derived more from its military implications than electricity generation.

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The biggest working fusion machine in the world by 2010 was the Joint European Torus, originally financed through the European Union, but now part of a much larger group. This was ready for action in 1983 at Culham; sited there because of the proximity of a large conventional power station supplying the national grid, complete with a special high capacity line across to the Jet machine. At Princeton there was built a similar machine, the Tokamak Fusion Test Reactor, also the JT-60 in Japan, and for many years these projects ran in parallel, intensely competing whilst learning from each other. By the mid 1980s there were 300 fusion research machines of all sorts operating in the world. Highly talented and motivated researchers were irresistibly attracted to this big science with its massive complex machines, long projects, international collaborations, all ultimately to produce something everybody wants or needs; a fine and honorable thing for them to get their intellectual teeth into. At Princeton the director of the TFRT poject, Harold Furth, felt obliged to issue a decree that nobody was to put in more than 84 hours of work per week. Most of his staff ignored him.

However, it is simplest to continue this complex story with Jet because that has led directly to what could be the definitive next experiment for fusion power. Tokamak is the format of Jet, but of compact ring shape, a cored apple rather than the traditional doughnut. The cross section profile of the tube is an upright rounded D and is up to 4 meters high whilst the torus ring is 6 meters diameter. Engineers during the first phases of experiments could easily walk inside the tube to modify the variegated structure of the inner wall of the tube. The tube is double walled so that the outer wall maintains the vacuum. The tube of the torus forms a vacuum chamber of 100 cubic meters and the plasma that forms within it occupies 60 cubic meters. The air that is sucked from the vacuum chamber weighs the same as a bulky man; the gas to form the plasma is introduced as the thinnest of vapors, many thousands of times lower than atmospheric pressure, weighing the same as a postage stamp.

The outer aspect of the machine is dominated by a set of eight square-cut lumps of iron acting as limbs of a huge transformer. These are connected to a single core passing through the center of the torus ring. Around this central core is sleeved the inner poloidal field coil. When powered up this transformer circuit induces an enormous current, seven million amperes, in the plasma. That in turn induces a poloidal field in the tube, which pinches the plasma away from the walls. Supplementary poloidal magnets, which help to control the shape and position of the plasma, consist of six circular magnets fitted horizontally around the outside of the torus ring. Around the circumference of the tube are thirty two D shaped magnets that create a toroidal field in the plasma running along the length of the torus ring. This toroidal field is ten times stronger than the basic poloidal field so the combined fields spiral slightly around the torus ring. The total magnetic force exerted on the plasma is four to five Tesla, about 100,000 times the force of gravity on Earth. At that strength the electrical circuits for the magnets need to be water cooled. Heating of the plasma is by a combination of resistance heating of the current induced in the plasma; by radio frequency energy pumped in; and by neutral beam injectors which accelerate uncharged atoms at high speed into the plasma, also pushing it round the ring. Temperature of the plasma can climb to 400 million degrees, and energy confinement time to nearly four seconds. Clearly, the design has evolved from the best of concepts developed in the Stellarator, Zeta and the T-3 tokamak.

The machine is operated in brief experimental pulses or shots. When there is electricity to spare from the national grid a pair of flywheels are set spinning to 225 revolutions per minute by an eight megawatt electric motor so that the rim is moving at 380 kilometers per hour. Very close to the rims are the windings of an electricity generator. When the switches are thrown the stored energy in the 750 tonne wheels is dumped into the generator and converted into 400 megawatts of electrical power capable of firing the torus for up to 20 seconds. A shot, with all the power for the magnets, plasma heating and ancillary equipment, needs 900 megawatts, which is most of the output of a typical large power station.

Jet is a long term experimental reactor with much work still to achieve. It is built as modules, think of segments of an orange, so the eight part structure of the vacuum chamber can be changed substantially. The entire machine is surrounded by a vast and bewildering array of up to fifty different working and experimental monitoring devices, masking the torus. All the while, its eight massive transformer limbs remain the enduring recognizable element; awkward elbows painted dull red, incongruously contrasting with so much shiny steel of advanced technology.

Fuel in early days was deuterium only. The potentially more effective reactions of deuterium plus tritium were not introduced until later because tritium, being radioactive, is difficult to handle. More importantly, reactions with tritium produce large fluxes of high energy neutrons. Crucially, these will be the means by which most heat is extracted from a normal working fusion reactor. The uncharged neutrons are so small and fast that they penetrate the thick metal walls of the tube. In a working power generator they will then collide with a thick blanket of lithium metal around the entire tube. That will absorb the neutrons and heat up. The heat will be extracted by pumping helium gas through channels in the lithium blanket. This in some ways is a beneficial cycle. The neutron transmutes some of the lithium into tritium, which forms fuel for the plasma reactions. Furthermore the very valuable helium is the waste product of the fusion reactions, thus a self-supply chain is inherent in the design.

Unfortunately, the neutrons will transmute a fraction of the metal walls of the tube into radioactive materials. Not so strongly that it will be a waste problem similar to that of fission power stations, but nevertheless creating severe problems for maintenance. So a major role of the Jet project has been to develop remote handling methods for the inside of the torus where human engineers will no longer be safe. Robotic arms 10 meters long and able to carry half a tonne reach into the tube. Engineers control the robot using a hands-on system with sensory feedback to place delicately all sorts of components.

With tritium added, the power available from the machine comes close to the power pumped in. But very briefly, four seconds. By 2005, for 25 megawatts of electrical power supplied by the coal-fired power station, the fusion reactor produced 16 megawatts: an efficiency quotient of 0.64. For a self sustaining working fusion power station the quotient obviously needs to be much higher than the balance point of 1. There is a long way to go, but steady progress from the T-3 tokamak through to Jet can be compared with the computer industry. Graphs demonstrating Moore’s law, about the number of transistors on a computer chip doubling every two years, are paralleled at a higher level by the line for numerous fusion machines across the world, with a doubling period of the crucial efficiency characteristic of 1.8 years. However, comparisons with the electronics industry should not be pushed to far because at every point on the graph for computer chips something useful for customers was available for sale.

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When the Iter machine is built in France it will be far bigger. The greater the chamber volume the easier it is to keep the plasma hot enough for sustained fusions. Thus the simplest comparison with Jet is the volume of the vacuum chamber formed by the tube of the torus: up from 100 to 837 cubic meters. Electrical efficiency will be much greater because the circuits and magnets will operate at minus 270 degrees, cooled by liquid helium to make them superconducting. Close by the exceedingly cold magnets, the heat of the plasma should approach 400 million degrees, with a current of 15 million amps surging through it. The efficiency quotient of the operating machine is expected to be 10, with 400 megawatts of power produced for an input of 40 megawatts. It should be possible to sustain this output for four seconds whilst the plasma is confined before its inherent tendency to turbulence sends it crashing onto the walls of the tube. Iter will have only small portions of a lithium blanket to test the absorption of useful heat because this remains an experimental project. A further machine, a prototype provisionally called Demo, has been planned for construction possibly starting in 2035. By 2050 it is hoped that the problems of the huge and complex system for actually extracting heat from the machine and driving an electricity generating turbine with it will have been solved. The engineering difficulties are already immense, even before any attempt has been made to extract useful heat from these machines. The prospects for doing that are mind boggling. When that problem has been solved work can start on building the first fusion power plant to deliver electricity to customers.

A lot hangs on this. Although there are varied smaller fusion projects continuing across the world most eggs are now in one basket with Iter, which is financed and run by a consortium of partner countries: China, European Union, India, Japan, Republic of Korea, Russia and United States of America. They will contribute from the intellectual and material resources of more than half the world's population. In its social, political and scientific ambitions this is a totally unprecedented endeavor.

The final slope to climb will be the steepest. For a commercial power station all this incomprehensibly complex, one-off, high technology will need to become so standard that it runs the way a carbon or uranium-fueled reactor does: day after day, decade after decade, with scheduled shutdowns for routine maintenance made possible because of redundant capacity of other generators embedded within a national or international electricity grid. Fission nuclear power is still, after many decades, only now becoming an enticing way for private companies to make a profit. Commercial companies lost interest in the profit-making potential of fusion by the 1980s. If a detailed article about generating electricity in a magisterial newspaper for business people, *The Economist,* is anything to go by they never will regain it, dismissing fusion power as: '. . . that favourite of fantasists . . .'.

It is sometimes claimed that the highly centralized nature of fusion power stations goes against the grain of the decentralized nature of wind, wave and geothermal renewable resources and small power stations fired with natural gas. However, most national strategies for power generation now propose a wide mix of systems. The need remains crucial to develop renewable systems to extract energy from the Sun, a source that will last an inconceivable span into the future. Fission power is limited by the extractable supplies of uranium, then the currently little used thorium, as a nuclear fuel. Several hundred year's worth, but possibly thousands of years if fission breeder reactors can be developed from experiment to power station. Fusion power is not strictly renewable either, a fusion reactor will slowly transmute the lithium blanket into crucial tritium and less crucial elements. Lithium deposits as extractable minerals are scarce relative to anticipated demand; possibly a thousand years worth, although there is much controversy about this. In addition lithium salts occur dissolved in seawater but the costs of extracting them would be huge. Moreover, there will not only be severe competition for this resource from manufacturers of lithium-ion batteries. The biggest deposits of mineable lithium occur in dry salt beds in the Andes, mainly Bolivia. Estimates of global reserves are issued as if all the material is readily available for trade on the open commercial market.

A heavy irony could develop, with prospects of non-polluting transport by electric vehicles using lithium based batteries in huge amounts in competition with an environmentally more benign replacement for fission power stations. The supply of tritium is also very problematic, it is produced as part of these transmutations in the lithium blanket, in what is known as a breeder reaction, but there will be hardly any to spare. So a reactor based on deuterium—tritium fusion can be considered as needing two fuels, deuterium concentrated from water, and lithium from mined rocks and salt beds. Only deuterium—deuterium fusions, which are much more difficult to start and sustain, can be regarded as having enough fuel to last beyond our imaginings.

Keep imagining: stick to the easier method currently proposed. The debate over the funding of fusion power is now shifting to whether humanity can afford both approaches. One choice is a colossal investment in genuinely renewable sources, all based on the daily energy that the Sun blesses the Earth with in amounts far exceeding anything we could ever need. That would have to be combined with similar investment to encourage fundamental changes in individual lives toward drastically lower consumption of both energy and material resources. Such a social transformation is difficult to believe possible in the time and degree necessary to avoid these shortages.

Despite all the enthusiasm for renewable energy, it seems nearly impossible to obtain as much energy from it as we currently use from conventional sources. An alternative is a technological solution at the far margins of our inventive genius to provide vast amounts of base-load electricity from nuclear fusion, to be supplemented with electricity from every renewable means possible, all in a civilization adapted to sparingly careful use of energy supplied mainly as electricity. Meanwhile, the remaining stocks of coal, oil and natural gas would be rationed for use as chemical feedstock and for transport uses where only fuels of high energy density are feasible.

Fusion power is project stretching from the first patent in 1946 to the planned prototype of 2050. What, for comparison, is the perspective? Human civilization is a longer term project, measured in millennia. From the start in the early 1800s of mechanized fuel use in agriculture and industry, we now have reached the era of arguing about whether oil and natural gas will last for another hundred years. Similarly, coal will last for several hundred years at current rates of consumption;

but not if used also to convert into substitutes for oil and gas. Clearly, the era of fossil fuels to power civilization is ephemeral in terms of human history. Furthermore, this is a short term future that we can only face with equanimity whilst ignoring both the likelihood of resource wars, and fantasizing that predictions of global warming due to our release of carbon dioxide are false. The physicists and engineers working on fusion power are now thinking in time spans that are both unique in the history of technology and appropriately respond to the enormity of the problem we face. They understand that without alternatives to fossil fuels human civilization will collapse.

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Generation of power beyond dreams, by means of nuclear fusion, was predicted in 1922 by Francis Aston after his successful experiments to explain the problem of the mass defect. His very tentative prediction was in sense vindicated, but not at first on Earth. The understanding and technical competence of nuclear physicists that developed in the 1920s was soon to be applied to the question of what supplies the vast energy of the Sun and stars. The observational proof that nuclear fusions provide the energy was difficult and confusing because the reactions are so complex, but experimental proof of Aston’s prediction came with that ghastly Sun-on-Earth, the fusion bomb at Enewatak atoll, in 1952. Eventually, by the 1990s, heat producing fusions in experimental reactors could be measured in seconds rather than milliseconds and engineers became gradually more important than physicists to substantiate the dream of fusion power.

The possibility of atomic nuclei fusing and transmuting into other elements, either naturally or by artifice was a concept that crept up on physicists probing into the center of the atom’s nucleus. What was it made of? If it is made of particles with mass then how many different particles are there and how do they behave, why do they form a nucleus, a different one for each element with its unique properties? This body of knowledge and understanding, by 1922, had grown rapidly into an interconnected school of thought, generated from the frontier studies of several hundred researchers in a score of centers and countries.

Thus Aston’s superb technical talent enabled him to construct and operate the relevant apparatus and then be the first to solve the mass defect problem, but if he had not answered this obvious question somebody else soon would have done so; Arthur Dempster in Chicago probably. The answer would have crystallized out from the rich saturated ferment of ideas at that time. This was no case of serendipity, no unexpected gleam of inspiration from a pile of facts contemplated by a lone researcher. Rather, it was the highly probable result of a diffuse but steadily determined push against the outer limits of understanding by the highest talents in physics at that time.

Nuclear fusion! Well now, look at what we have all revealed, in this mass-effort dig at the archaeological site of the atomic nucleus. Admire this treasure chest of future research adventures.

Contrast the fortunes of the nuclear fusion business with that of nuclear fission. The first clues came from Enrico Fermi, determined to make a name for himself with the latest research tool of bombarding materials with beams of those newly discovered neutrons. Embarking on a massive fact finding study, he worked his way through much of the periodic table, along a scale of increasing atomic weight until finally he got to uranium. His results with this heaviest of natural elements was totally unexpected and inexplicable, beyond all available understanding of atoms and their nuclei. This was a mystery that had to be solved, but even those who revealed it – Meitner, Frisch, Hahn and Strassman – were doubtful of their interpretation. How could a nucleus actually split in two, and seemingly regress by transmutation to two nuclei of the element of half the weight of uranium; surely too simple an explanation? Their faith in their data was justified, as Fermi and team with their famous pile of nuclear bricks in the university stadium were soon to prove. Within less than twenty years nuclear fission reactors were delivering electricity to several national grids.

Is there an explanation for the difference between these two outcomes? Elliott W. Montroll has provided a mathematician's answer, as an example of the causes and consequences of power laws in the natural and manufactured worlds. He described the problem as it relates to invention as: 'the tyranny of many dimensionless constants.' During the rapid development of working fission power generators the problem could be compartmented into groups of two or three dimensionless physical constants (no units) which were manageable to model. In contrast, the complex behavior of plasmas, and the structures required to tame them, involve about eight interacting dimensionless constants whose modeling becomes exceedingly complex. Thus the probability of some genius inventor being able to go directly to the single solution decreases exponentially with the number of such constants. The complexity has increased since Montroll wrote that.

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